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## DATA ANALYSIS FOR NEUTRON MONITORING IN AN ENRICHMENT FACILITY

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### Abstract

Area monitoring of neutron radiation to detect high-enriched uranium production is a potential strategy for inspector verification of operations in the cascade area of a centrifuge enrichment facility. This paper discusses the application of statistical filtering and hypothesis testing procedures to experimental data taken in an enrichment facility. The results demonstrate that these data analysis methods can enhance detection of facility misoperation by neutron monitoring.

### 1. Introduction

International safeguards for enrichment facilities must include strategies for assuring that the facility is not misoperated to produce highly enriched uranium (HEU). Several potential radiation monitoring strategies sensitive to HEU production are presently under consideration for inspector use in gas centrifuge enrichment facilities. These methods consist of neutron and gamma monitoring to detect anomalous increases in the radiation environment of the cascade area. One strategy employs continuous monitoring of neutron levels with  $^3\text{He}$ /polyethylene detectors mounted at fixed positions in the cascade area. Since June 1980, a prototype neutron monitor system,<sup>1,2</sup> including four monitor stations and a minicomputer-based data acquisition station, was operated nearly continuously at US centrifuge development facilities at Oak Ridge, Tennessee. Since June 1981, two additional monitors have been operating at URENCO centrifuge facilities at Almelo, the Netherlands. This report describes data analysis procedures that can enhance the information extracted from neutron measurement data.

### 2. Experimental Results

Experimental data taken at the Advanced Engineering Test Facility in Oak Ridge has been used to test the proposed data analysis procedures. In these experiments, gas centrifuges similar to the type to be installed at the Portsmouth facility were operated at several levels of enrichment. A  $^3\text{He}$ /polyethylene fast neutron detector placed near the centrifuges measured the neutron level due to background and machine misoperation while a remote monitor provided a reference for the neutron background. The experiment consisted of periods of 16%, 52%, and 90% enrichment operation separated by periods of off-gas operation. Selected measurement data from this experiment are given in Fig. 1, which describes the neutron level measured by one of the monitors near the misoperated centrifuges.

#### 1. Analysis Procedures

Continuous monitoring of neutron levels in the cascade area provides an inspector with the

means for timely detection of anomalies in cascade area operations. Further, where a sufficient number of these monitors are located throughout the cascade area, the source of the anomaly may be localized. The proposed analysis procedure estimates the true neutron level from the noisy measurements and detects when that level has increased sufficiently that an anomaly should be declared. This paper discusses the application of statistical filtering to neutron signal estimation and statistical hypothesis testing to detect abnormal signal increases. The hypothesis testing procedures are structured to control the detection and false-alarm probabilities.

Detection of HEU production by the proposed neutron monitoring system is considered to be a problem in statistical hypothesis testing. The hypothesis  $H_0$  of a neutron level indicating normal operation is tested against the alternative hypothesis  $H_1$  of an increased neutron level. Testing these hypotheses require the conditional probability densities of the neutron measurements  $Z_1, \dots, Z_N$  under each hypothesis. If  $H_0$  is true, the probability density is  $p(Z_1, \dots, Z_N | H_0)$ ; similarly, if  $H_1$  is true, the probability density is  $p(Z_1, \dots, Z_N | H_1)$ . A test procedure for deciding between  $H_0$  and  $H_1$  is the probability ratio test.<sup>3</sup> The probability ratio for the measurement sequence is

$$PR(N) = \frac{p(Z_1, \dots, Z_N | H_1)}{p(Z_1, \dots, Z_N | H_0)}$$

This ratio is a number that measures the relative likelihood of the two hypotheses given the measurements. Larger values of  $PR(N)$  favor  $H_1$  and smaller values favor  $H_0$ . The test procedure

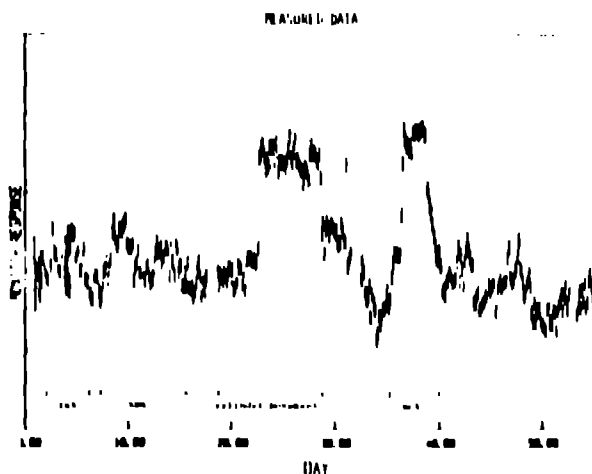


Fig. 1. Experimental data.

consists of comparing the probability ratio to an upper threshold TU and a lower threshold TL and applying the decision rule

accept  $H_1$  when  $PR(N) \geq TU$

accept  $H_0$  when  $PR(N) \leq TL$

and take another measurement and continue testing otherwise. When the hypotheses  $H_0$  and  $H_1$  are simple (they completely specify the conditional densities), the probability  $\alpha$  (false-alarm probability) of accepting  $H_1$  when  $H_0$  is true and the probability  $\beta$  (miss probability) of accepting  $H_0$  when  $H_1$  is true are approximated by defining the thresholds

$$TL = \frac{\beta}{1 - \alpha} \quad \text{and} \quad TU = \frac{1 - \beta}{\alpha}.$$

The formulation of the problem of detecting HEU production leads to the composite hypotheses

$$H_0: u = u_0$$

and

$$H_1: u > u_0,$$

where  $u_0$  is the expected neutron measurement when  $H_0$  is true and  $u$  is the true neutron level. The usual way of treating the probability ratio test when hypotheses are composite is to form the generalized probability ratio

$$GLR(N) = \frac{\max_{u > u_0} p(Z(N)|u)}{\max p(Z(N)|u_0)}.$$

#### 4. Statistical Filtering

Filtering<sup>4</sup> is a method for estimating the current value of a signal using noisy measurements of the signal. Applying this method to estimate the neutron signal from the uranium inventory of enrichment centrifuges requires an estimate of the neutron background measured by the detector. For this analysis the remote monitor background measurements were used to estimate the background for the centrifuge monitor. The measurement model for the remote monitor is

$$x_N = BG_N + a_N,$$

where  $BG_N$  is the true but unknown background at the remote monitor and  $a_N$  is the measurement error. The error model for the centrifuge monitor is

$$y_N = s_N + (a_N \cdot BG_N + b_N) + \beta_N,$$

where  $y_N$  is the measurement,  $s_N$  is the neutron signal from the centrifuges,  $a_N \cdot BG_N + b_N$  expresses an assumed time-varying linear relationship between the background at the remote and centrifuge monitors, and  $\beta_N$  is the measurement

error. Estimating the background at the centrifuge monitor by  $\hat{a}_N \cdot \hat{x}_N + \hat{b}_N$ , where  $\hat{a}_N, \hat{b}_N$  are estimates of  $a_N, b_N$ , and subtracting this from  $y_N$  gives

$$z_N = s_N + \gamma_N,$$

where  $\gamma_N$  is an error term that depends on  $a_N, \beta_N$ , and the uncertainty in estimating the coefficients  $a_N, b_N$ . The statistic  $z_N$  is the object of the filtering procedures to estimate  $s_N$ .

The Kalman filter provides an estimate of the true value of a signal that is embedded in noise. Application of the method requires a model of the signal as a function of time and a model of the noisy observations of the signal. For this problem the signal is assumed to be constant

$$s_{N+1} = s_N,$$

and the observation model is

$$z_N = s_N + \gamma_N, \quad (1)$$

where  $\gamma_N$  is the measurement error. The only knowledge of the signal is through the noisy measurement relationship in Eq. (1).

The filter estimate of  $s_N$  is a weighted linear combination of the observations  $z_1, \dots, z_N$ . This linear estimate can be expressed in the recursive form

$$\hat{s}_N = \hat{s}_{N-1} + K_N(z_N - \hat{s}_{N-1}),$$

where  $\hat{s}_N$  is the signal estimate at time  $N$ . The filter gain  $K_N$  is calculated from

$$K_N = \frac{V_N}{V_N + W_N},$$

where  $V_N$  is the variance of the estimate  $\hat{s}_N$  and  $W_N$  is the variance of  $\gamma_N$ .

The Kalman filter method provides a minimum-variance, unbiased estimate of the true neutron signal from the centrifuges. When this estimate exceeds the neutron level for normal enrichment by twice the standard deviation of the estimate, there is an indication of an anomaly. However, the decision between  $H_0$  and  $H_1$  should be made using the probability ratio test that allows control of the error probabilities. The Kalman filter method is used to estimate the unknown quantities in the conditional probability densities in the probability ratio.

#### 5. Data Analysis Results and Conclusions

The experimental data in Fig. 1 have been analyzed using both filtering and hypothesis testing procedures. Filtering of the data is represented in Fig. 2, which is the Kalman filter estimate of the neutron signal from the centrifuges. The estimate is centered at the 12

standard deviation error bars. Periods of increased enrichment are identified as positive deviations of the signal estimate by more than 2 standard deviations from the zero neutron signal level.

The probability ratio for deciding between  $H_0$  and  $H_1$  is plotted in Fig. 3. Upper decision thresholds have been selected for approximate false alarm rates of 0.01 and 0.001. When the probability ratio exceeds the upper threshold, detection of an anomaly is declared. Enrichments of 52 and 90% are easily detected at the 0.001 level. Enrichments of 20% could be detected at a false-alarm rate somewhat higher than 0.01.

These results suggest that statistical filtering and hypothesis testing procedures can be useful to an inspector for extracting information about facility operation from noisy measurement data. The filtering methods can estimate neutron signals from enrichments near 20%, and hypothesis testing procedures can detect enrichments near 20% with a false-alarm rate between 0.01 and 0.001 per year.

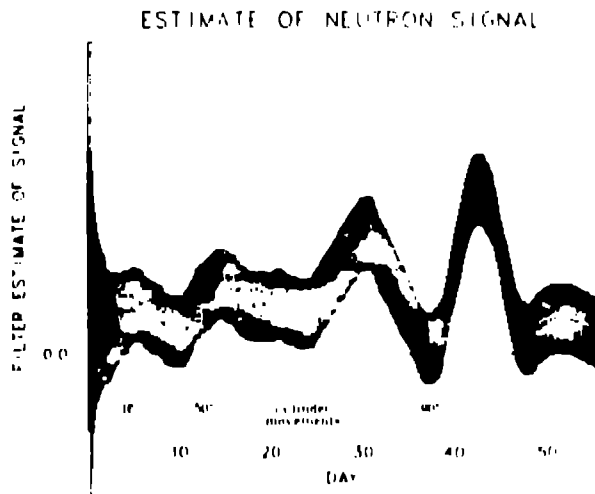


Fig. 2. Filtered data.

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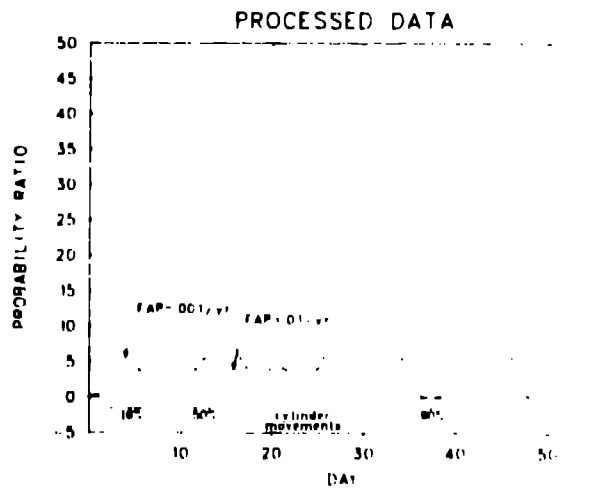


Fig. 3. Probability ratio test results.